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CALCULATION AND DESIGN OF GLASS MELTING TANKS FOR GLASSMAKING FURNACES FOR CONTAINER GLASS

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The procedure for calculating and designing melting tanks for glassmaking furnaces used in the manufacture of container glass is examined. It is shown that mathematical modeling of the internal heat and mass transfer makes it possible to increase substantially the quality of the design solutions, whose implementation creates objective prerequisites for attaining a high energy efficiency and productivity for glassmaking furnaces.

Key words: glassmaking furnace, glass melting tank, heat-transfer parameters, boundary conditions, masonry structure.

Efficient use of the heat energy transferred to the tank as a result of the external heat transfer and intended for implementing the technological process is the main requirement for designing melting tanks. The results of mathematical simulation of the external and internal heat and mass transfer [1] show that in high-productivity glassmaking furnaces even with a flat flame of optimal length the maximum temperatures to which the surfaces of the molten glass and masonry are heated are comparable to their limiting values for refractories in the working space and melting tank. Hence it follows that it is practically impossible to increase the specific productivity of a furnace without intensifying internal heat and mass transfer and minimizing the heat losses through the masonry of the tank.

Heat transfer from the high-temperature zone of the tank to its less heated parts is largely determined by the tank's hydrodynamics. In addition, because of the technical features of the glassmaking process it is best to redistribute the heat in the furnace loading direction. The external heating conditions limit the possibility of increasing the temperature of the tank's surface in the melting zone of the mix piles. For this reason, intensification of the glass-forming reactions in flame furnaces without additional electric heating becomes possible only if the temperature of the molten glass is increased in this part of the tank by intensifying heat transfer by means of the convection flow of the free-flow cycle.

In taking account of production flow, the effect of the temperature gradient at the surface of the molten glass on the organization of the convection field of the melt is limited. Creating the conditions for a clearly defined convection flow of the free-flow cycle with counterclockwise rotation of the molten glass is a very important function of the melting tank. Increasing melt circulation in this loop is of fundamental importance for heat-transfer and the residence time of melt in the tank. Heat exchange on the right-hand side of the melting tank is determined not only by the boundary conditions on free and forced convection but also on the structural components of the tank which impede melt flow. Therefore, the design of the melting tank must take account of the organization of the convection flow of the process cycle. On the technological level, the evaluation of this flow can be based on two basic requirements. They concern the time that the melt resides in this part of the tank and the thermal uniformity of the molten glass extracted for production. Under the conditions being compared both characteristics are determined by the number of times the molten glass circulates in this loop.

In general, the calculation and design of a melting tank reduce to determining its geometric dimensions and the structure of the masonry of the protective surfaces. We shall examine the procedure used to design a melting tank for a concrete example. The initial data are assumed to me as follows.

The productivity of the furnace $P_f = 300$ tons/day and the specific extraction of molten glass is $P_{sp} = 2.6$ tons/(m² · day). Hence the area of the melting tank is

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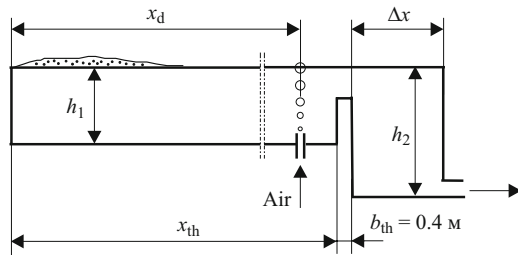


Fig. 1. Schematic of the melting tank: h_1 and h_2) height of the shallow and deep parts of the tank, respectively; x_b and x_{th}) distances from the left-hand wall of the tank to the bubbling axis and the threshold, respectively; b_{th}) width of the threshold; Δx) distance from the right-hand side of the tank to the threshold.

$F_f \approx 115.4 \text{ m}^2$. The ratio of the length and width of the tank is determined by the condition $L_f/B_f = 1.5 - 1.7$; for the average value of L_f/B_f we have

$$L_f = \sqrt{(1.5-1.7)F_f} = 13.62 \text{ m}.$$

The chemical composition of ZT-1 glass is (%²): 71.90 SiO₂, 2.00 Al₂O₃, 0.20 Fe₂O₃, 9.60 CaO, 2.20 MgO, 13.10 Na₂O, 0.55 K₂O, 0.25 Cr₂O₃, 0.20 SO₃.

The temperature distribution on the surface of the molten glass is as follows. For glassmaking furnaces with a horse-shoe flame arrangement and optimal flame length equal to the length of the tank the boundary conditions for free convection can be set by the equation [1]

$$\bar{t}_g(x_1) = 1236.3 - 30.112x_1 + 1274.6x_1^2 - 613.08x_1^3 - 539.06x_1^4,$$

where $x_1 = x/L_f$ and x is the longitudinal coordinate of the melting tank, m.

It follows from the last equation that for $L_f = 13.62 \text{ m}$ the maximum temperature to which the surface of the molten glass is heated is 1508.7°C, and its arrangement along the tank is determined by the coordinate $x_{\max} = 10.0 \text{ m}$.

For the prescribed chemical composition of green glass the temperature dependence of the thermal conductivity of the glass and the refractory and heat-insulating materials is

$$\lambda_{\text{eff}} = \lambda_{\text{con}} + \lambda_{\text{rad}} = 1.0908 - 0.5 \times 10^{-3} t + 6 \times 10^{-6} t^2,$$

where λ_{eff} , λ_{con} , and λ_{rad} are the effective, conductive, and radiative thermal conductivities of the glass, W/(m · K), and t is the temperature of the molted glass, °C.

Choice of the Melting Tank Design. The results of the mathematical modeling of the heat and mass transfer and practical experience [1] show that the prescribed specific extraction of molten glass is accomplished using a tank design with a variable depth in the melting and fining zones, separated by an overflow threshold (Fig. 1). Swirling the melt

with compressed air is sufficient as an additional means of intensifying the circulation of the molten glass in the loop of the free-flow cycle.

At the initial step of the calculation we fix the following geometric dimensions of the tank (see Fig. 1): $h_1 = 1.3$, $h_2 = 2.5$ and $x_{th} = 11.2 \text{ m}$. Hence it follows that the characteristic length Δx and cavity depth ($\Delta h = h_2 - h_1$) in the fining zone are 2.02 and 1.20 m, respectively. The average temperatures of the surface of the molten glass in the melting zone (leftward of the threshold) and the fining zone (behind the threshold) are $t_{\text{mg}} = 1369.1$ and 1415.3°C , respectively. The height and width of the channel are taken to be 0.3 and 0.8 m. Therefore, the average flow rate of the glass mass in the channel is 3.47 kg/sec.

Structure of the Melting Tank Masonry. It is well known that any increase of the specific extraction of the molten glass decreases the residence time of the primary melt in the tank, which to a certain extent depends on the ratio of the volumes of the extracted molten glass and the amount of molten glass in the tank. It can be supposed that for $F_f = \text{const}$ an increase of P_{sp} presumes a directly proportional increase of the tank depth. This condition may not hold, if the thickness of the layer of molten glass and the efficiency of the heat insulation at the bottom of the melting tank increase at the same time. Then the attained increase of the average temperature of the molten glass will intensify glassmaking and fining processes, which to a certain extent compensates the decrease of the residence time of the primary melt in the tank.

The combination of the melting tank depth and the requirements for heat insulation at the bottom of the tank is shown in [2]. For constant surface temperature of green glass ($t_{\text{mg}} = 1450^\circ\text{C}$) a systematic increase of the tank depth from $h_{\text{mg}} = 0.8$ to $h_{\text{mg}} = 1.1$ and 1.4 m changes the thermal resistance of the bottom masonry from $R = 0.11$ to $R = 0.6$ and $1.0 \text{ m}^2 \cdot \text{K/W}$, respectively. These values of R correspond to the temperature of the tank bottom $t_{\text{tb}} = 950$, 1240 , and 1280°C and heat flux into the surrounding medium $q_{\text{sur}} = 5800$, 1800 , and 1100 W/m^2 . This gives a considerable decrease of the temperature gradient over the thickness of the layer of molten glass. For the present example $t_{\text{mg}} - t_{\text{tb}}/h_{\text{mg}}$ decreases from 625.0 to 190.1 and 121.4 K/m , respectively.

It should be noted that the assessment of the tendency for the tank depth to increase is by no means unique. This assessment is positive in respect to the “formal” action on the duration of the glassmaking process. If one considers the possibility of further raising the bottom and average temperatures of the molten glass via the quality of the insulation of the bottom, then for deep tanks it is exhausted. Moreover, high-temperature glassmaking in a deep and well-insulated tank does not guarantee that the specific productivity of the furnace will be high. One should not forget that the construction of melting tanks is complicated and such tanks with a deep fining zone are expensive. For this reason, the determination or confirmation of the prescribed parameters of the

² Here and below — content by weight.

depth of the glassmaking and fining zones should be regarded as the most important step in designing a melting tank. The operating conditions of the tanks with glass being extracted and with the glass-forming machines shut down must be taken into account.

Together with the free- and forced-convection boundary conditions the tank depth is also determined by the optical density of the melt and the technological requirements for the temperature of the bottom layer of the molten glass. The latter condition is inextricably tied to the operational stability and thermal resistance of the bottom masonry of the melting tank. It is known that a high temperature of the molten layer of glass at the bottom accelerates corrosion of the refractory materials in contact with the melt and decreases the service life of the furnace. At the same time a low temperature level results in the formation of a lining slag layer at the bottom of the tank, which creates the prerequisites for quality degradation of the molten glass.

We shall now formalize the requirement for the efficiency of the heat insulation at the bottom of the tank. Experience has shown that the average temperature of the bottom layer of the molten glass in the melting and fining zones in the presence an extraction flow is at least 1250 – 1300 and 1399 – 1350°C, respectively. A more difficult problem is to determine the minimum melt temperature for free convection conditions (no extraction of molten glass), for which the heating of the tank is in accord with stationary heat conduction. This temperature must correspond to a flowing state of the glass. It must be related with the chemical composition of the glass and have a reasonable computed value. In our view, one of the characteristic temperatures on the viscosity curve of the glass satisfies these conditions, for example, the temperature of the molten glass with extraction (temperature of a drop of glass), corresponding to dynamic viscosity $10^2 \text{ Pa} \cdot \text{sec}$. For a prescribed chemical composition of the glass it is 1204°C. Therefore, the minimal temperature of the melt at the bottom of the tank can be taken as $t_{\min} \approx 1200^\circ\text{C}$.

We shall now examine one possible variant of the construction of the tank bottom of a high-productivity glass-making furnace [3]. In the multilayer structure of the masonry (Fig. 2) the purpose of the layers 1 – 6 is to ensure safe operating conditions for the melting tank. The first layer of the masonry, which is in contact with the melt, is made of electrofused baddeleyite-corundum refractory. The average density of the slab without a shrinkage cavity is 3.65 tons/m^3 . Its thickness can vary in the range 100 – 150 mm. The slab is separated from the rest of the masonry by two layers of unformed materials with usage temperature 1650°C , which seal the surface of the tank bottom and increase its corrosion resistance to the glass melt and drops of metal.

The main safety layer (layer 3) consists of a coarse-grain zircon – mullite mixture (18% ZrO_2 , 68% Al_2O_3). When the mixture is heated, glass-stable mineral phases characterized by strong bonds with the electrofused refractory AZS are formed. Before the AZS slab is installed, a fine-grain solu-

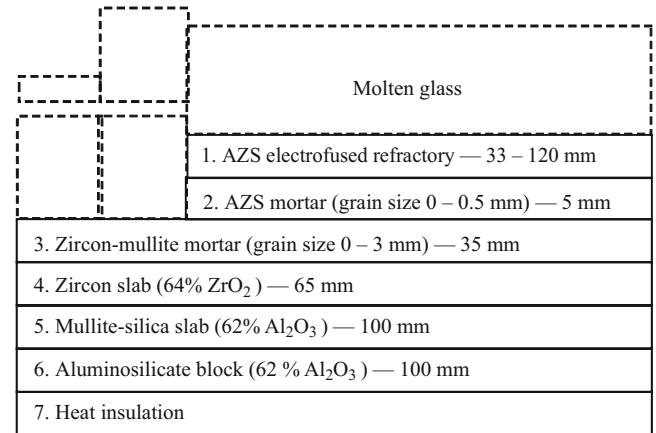


Fig. 2. Arrangement of the bottom masonry of a melting tank.

tion of AZS mortar (layer 2) with a high content of zirconium oxide (31% ZrO_2 , 49% Al_2O_3) is laid on this layer. The subsequent layers (4 and 5) of the refractory masonry increase the corrosion resistance of the tank bottom with possible breakthrough of the glass melt and metal through the AZS slab and the sealing layers of mortar. The bottom masonry is completed by a large, 0.2 m thick, aluminosilicate bottom block.

The heat insulation of the tank bottom (layer 7) can be single- or multilayered using materials with different density and thermal conductivity. As a rule, light-weight aluminosilicate articles with apparent density $0.4 – 1.3 \text{ tons/m}^3$ or analogs made abroad are used as insulation materials. Light-weight LEGRAL 40/2 with density 1.3 tons/m^3 (density analog of the refractory ShL-1,3) and thermal conductivity close to that of the refractory ShL-0.9 is used in our example.

We shall determine the thickness of the insulating layer of the masonry at the bottom of the tank, giving t_{\min} for $h_1 = 1.3$ and $h_2 = 2.5 \text{ m}$, as well as with free-convection boundary conditions and prescribed temperatures $t_{\text{mg}} = 1369.1$ and 1415.3°C . Heat transfer is calculated using the stationary heat-conduction an equation

$$q_{\text{out}} = \frac{t_{\text{mg}} - t_{\text{sur}}}{\frac{h_{\text{mg}}}{\lambda_{\text{eff}}} + \sum_{i=1}^n \frac{S_i}{\lambda_i(t)} + \frac{1}{\alpha_{\text{out}}}},$$

where t_{sur} is the temperature of the surrounding medium (40°C), S_i and $\lambda_i(t)$ are the thickness and thermal conductivity of the i th layer of the masonry at the tank bottom, m and $\text{W}/(\text{m} \cdot \text{K})$, respectively; α_{out} is the heat convection coefficient at the laying face of the tank bottom (natural convection), $\text{W}/(\text{m}^2 \cdot \text{K})$; and, n is the number of layers in the masonry.

The computational results for the heat transfer in the melting zone show that in the absence of thermal insulation at the bottom $R = 0.48 \text{ m}^2 \cdot \text{K}/\text{W}$. The bottom temperature

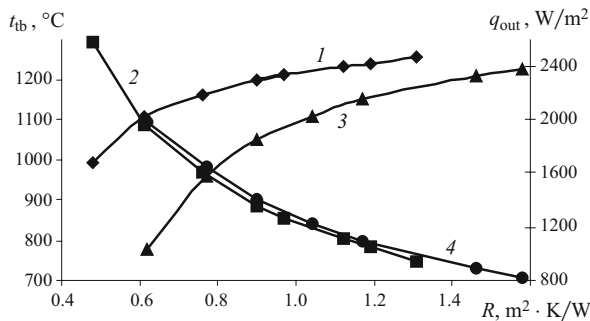


Fig. 3. Effect of the thermal resistance of a layer of green glass and masonry at the tank bottom on the bottom temperature of the melt (1, 3) and heat flux into the surrounding medium (2, 4). The numbers of the curves correspond to the row numbers: 1, 2) $t_{mb} = 1369.1^\circ\text{C}$, $h_{mg} = 1.3\text{ m}$; 3, 4) $t_{mg} = 1415.3^\circ\text{C}$, $h_{mg} = 2.5\text{ m}$.

990.5°C (Fig. 3, row 1) and its gradient 291.2 K/m show that the thermal resistance of the main masonry at the bottom (see Fig. 2, layers 1 – 6) does not give the required value of t_{min} . As a result, large losses of heat to the surrounding medium (see Fig. 3, row 2) and high temperatures at the outer surface of the tank bottom are observed: $q_{out} = 2578.0\text{ W/m}^2$ and $t_{out} = 193.5^\circ\text{C}$. In the fining zone the following heat-transfer parameters correspond to $R = 0.62\text{ m}^2 \cdot \text{K/W}$: $q_{out} = 1979.1\text{ W/m}^2$, $t_{tb} = 776.8^\circ\text{C}$, and $t_{out} = 168.4^\circ\text{C}$.

The required heat-insulation efficiency in the melting zone with free convection is achieved with LEGRAL 40/2 layer thickness 0.195 m. An increase of R from 0.48 to $0.9\text{ m}^2 \cdot \text{K/W}$ results in the following: $q_{out} = 1363.4\text{ W/m}^2$, $t_{tb} = 1197.5^\circ\text{C}$, $t_{out} = 138.7^\circ\text{C}$ and $t_{mg} - t_{tb}/t_{mg} = 132.0\text{ K/m}$. In the fining zone the thermal resistance of the tank must be increased to $1.43\text{ m}^2 \cdot \text{K/W}$. For heat-insulating layer thickness 0.38 m (see Fig. 3, rows 3 and 4) we obtain in this case: $q_{out} = 908.6\text{ W/m}^2$, $t_{tb} = 1203.4^\circ\text{C}$, and $t_{out} = 112.7^\circ\text{C}$ and temperature gradient over tank depth 84.77 K/m.

The side wall of the melting tank is divided into three sections according to the construction of the masonry (Fig. 4). Its top part (200 – 250 mm) is not insulated and is force-cooled by air [4]. As a rule, air is supplied through 20 mm wide flat (slit-like) nozzles, arranged 50 mm from the cooled surface and making an angle 20° to the horizontal plane. Piece insulation is placed at the center of the wall (about 50% of the height of the palisade girder); the vertical seams where the AZS girders adjoin the break in the cold lining to 50 mm remain open. The lower part of the wall is covered with continuous heat insulation. The outer surface of the refractory blocks and the seams where they join are sealed with a 5-mm thick layer of fine-grain AZS mortar. It is recommended that 20% (above 100%) technical orthophosphoric acid with 45% concentration be added to the water solution of the mortar.

Modern materials make it possible not only to unify the structure of the discrete and continuous heat insulation (see Fig. 4) but also to ensure a considerable decrease of the heat

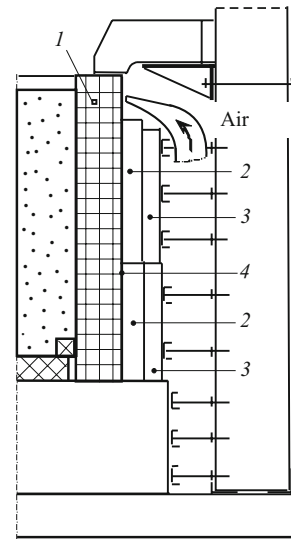


Fig. 4. Structure of the masonry of the side walls of the melting tank: 1) electrofused refractory AZS — 36(41) — 250 mm; 2) multi-lite-silica light-weight (58% Al_2O_3 , $\rho = 0.79\text{ tons/m}^3$, $t_{seam} = 1400^\circ\text{C}$) — 114 mm; 3) fiber batt ($\rho = 0.32\text{ tons/m}^3$, $t_{seam} = 1100^\circ\text{C}$) — 100 mm; 4) AZS mortar (grain size 0 – 0.5 mm) — 5 mm.

losses into the surrounding medium. In the melting zone the outer temperature of the piece and continuous insulation is 106.8 and 105.5°C and the heat flux does not exceed 967.3 and 942.3 W/m^2 , respectively. For the fining zone $t_{out} = 108.5$ and 106.7°C , $q_{out} = 1016.2$ and 965.3 W/m^2 , respectively. Taking account of the seams where the blocks adjoin (natural cooling) the average heat losses through the sections of the wall with piece insulation for the melting and fining zones is 2626.0 and 2715.4 W/m^2 , respectively [3].

In summary, the computational results for heat transfer through the tank for free-convection boundary conditions make it possible to set the preliminary arrangement of its profile. The construction of the masonry walls and the bottom of the tank is determined and the heat-transfer coefficients are refined. The latter are used as initial data for modeling the hydrodynamics and internal heat transfer in the presence of the extracted flow.

Mathematical Modeling of the Internal Heat Transfer and Hydrodynamics. The main objective of this step is to determine the correspondence of the computed internal heat transfer parameters to the prescribed furnace capacity or, on a wider plane, to the forced-convection boundary conditions. It is obvious that only the results of numerical modeling give a possibility of definitively determining the validity of the design solutions as a whole and with respect to individual structural elements of the melting tank. Specifically, this refers to determining the height of the threshold h_{th} and the channel h_{ch} as well as the locations of the bubbling setup x_b (see Fig. 1).

Tables 1 and 2 show the effects of the threshold height and the channel height on the internal heat transfer. Analysis

of data in these tables makes it possible to draw the following conclusions. First, we note that on the basis of the priority position of enthalpy of the molten glass in the melting zone the height of the threshold can be taken as 0.6 m, and the channel height retains its previously assigned value — 0.3 m. Taking account of the forced-convection boundary conditions increases the temperature of the tank bottom in the melting and fining zones by 110°C on average. The average temperature gradient over the depth of the molten glass decreases to 56.5 K/m. On the whole the melt temperatures at the bottom in the melting and fining zones (1311.2 and 1330.0°C, respectively) satisfy the requirements presented above. Finally, the integral-averaged temperature of the molten glass at the entrance into the flow (1348.3°C) can be regarded as a boundary condition when calculating the extracting channel.

In general, the hydrodynamics of a melting tank is determined by its geometric dimensions as well as by the free- and forced-convection boundary conditions [1]. Bubbling is used because it is necessary to intensify the circulation of the molten glass in the convection flow in the free-flow cycle. For this reason the location of this setup must correspond to the boundary between the free-flow cycle contour (x_b , see Fig. 1) and the local circulation contour, formed at the left-hand wall of the threshold (Fig. 5). The results of the modeling attest that for the tank and boundary conditions studied $x_b = x_{\max} = 10$ m, i.e., the position of the bubbling

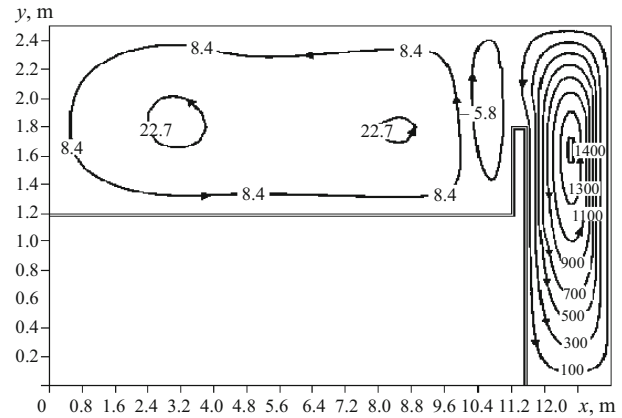


Fig. 5. Flow pattern of molten glass in a longitudinal section of the melting tank: $\Delta x = 2.02$; $\Delta h = 1.2$; $h_{th} = 0.6$; $h_{ch} = 0.3$ m.

setup is the same as that of the maximum temperature at the surface of the molten glass. The distance between the axis of the bubbling nozzles and the left-hand wall of the threshold is 1.2 m.

The equations formalizing the dependence of the parameters of the internal heat and mass transfer on the construction of the tank [1] makes possible a comparative analysis of designs with different fining zone depths. Technically, there is no doubt that tanks with a deep fining zone can be used to melt colored glasses. However, arguments supporting the de-

TABLE 1.

h_{th}, m	Computational parameters*				
	$t_{mg, ch}, ^\circ\text{C}$	$t_{2,1,2}/t_{2,1,1}, ^\circ\text{C}$	$t_{b,m}/t_{b,f}, ^\circ\text{C}$	$t_m/t_f, ^\circ\text{C}$	$R_T, \%$
0	1348.7	1259.0/1295.0	1301.1/1326.7	1314.6/1334.8	98.53
0.2	1348.2	1260.0/1298.0	1308.5/1327.9	1317.9/1335.5	98.61
0.4	1347.9	1260.4/1299.0	1308.7/1328.6	1319.1/1335.7	98.68
0.6	1348.3	1261.0/1300.0	1311.2/1330.0	1320.2/1337.1	98.76
0.8	1348.4	1258.8/1294.1	1304.0/1332.2	1313.1/1338.9	98.80

* $t_{mg, ch}$) integrated average temperature of the molten glass at the entrance in the channel; $t_{2,1,2}$ and $t_{2,1,1}$) molten glass temperatures at the points with the coordinate $x = 2.0$ and at depths 0.1 and 0.2 m from the surface of the tank; $t_{b,m}$ and $t_{b,f}$) average temperature of the molten glass at the bottom of the tank in the melting and fining zones; t_m and t_f) integrated average temperature of the molten glass in the melting and fining zones; R_T) thermal uniformity factor of the molten glass at the entrance into the channel.

TABLE 2.

h_{th}, m	Computational parameters				
	$t_{mg, ch}, ^\circ\text{C}$	$t_{2,1,2}/t_{2,1,1}, ^\circ\text{C}$	$t_{b,m}/t_{b,f}, ^\circ\text{C}$	$t_m/t_f, ^\circ\text{C}$	$R_T, \%$
0.2	1347.4	1260.6/1300.4	1311.2/1331.2	1320.2/1337.1	98.80
0.3	1348.3	1261.0/1300.0	1311.2/1330.0	1320.2/1337.1	98.76
0.4	1348.8	1260.7/1300.5	1311.4/1331.1	1320.3/1337.2	98.53
0.5	1349.0	1260.7/1300.6	1311.5/1331.0	1320.4/1337.0	98.56

TABLE 3.

Δh , m	Computational parameters				
	$t_{\text{mg.ch}}$, °C	$t_{2.1,2}/t_{2.1,1}$, °C	$t_{\text{b.m}}/t_{\text{b.f}}$, °C	$t_{\text{m}}/t_{\text{f}}$, °C	R_T , %
0.2	1347.6	1255.4/1279.2	1285.8/1311.4	1397.3/1323.3	98.58
0.4	1348.8	1256.6/1286.2	1294.4/1321.0	1304.8/1330.8	98.62
0.6	1349.2	1257.6/1290.0	1299.1/1326.2	1308.9/1335.1	98.66
0.8	1349.2	1258.4/1292.6	1302.2/1329.6	1311.6/1337.9	98.71
1.0	1348.8	1258.9/1294.6	1304.6/1332.1	1313.7/1340.1	98.76
1.2	1348.4	1259.4/1296.2	1306.5/1334.1	1315.3/1341.8	98.80

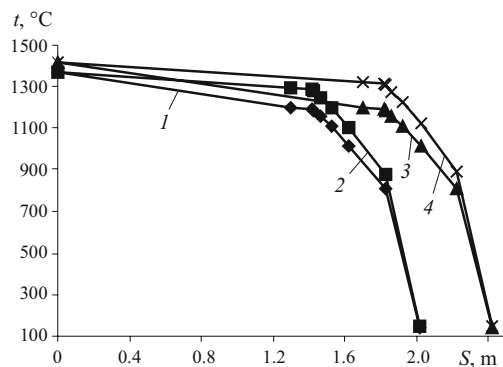


Fig. 6. Temperature distribution over the depth of the tank and bottom masonry. The numbers on the curves correspond to the row numbers: 1, 2) $h_{\text{mg}} = 1.3$ m; 3, 4) $h_{\text{mg}} = 1.7$ m; 1, 3 and 2, 4) free and forced convection, respectively.

sirability of such designs are needed. The effect of the cavity depth on the parameters of the internal heat transfer ($\Delta x = 2.02$ m) is reflected in Table 3. Using the data of Table 3 we shall compare the parameters of the internal heat transfer for two variants of the tank design: No. 1 — $\Delta x = 2.02$, $\Delta h = 1.2$ m and No. 2 — $\Delta x = 2.02$, $\Delta h = 0.4$ m. Strictly speaking, the deep cavity variant (No. 1) is preferable. At the same time it should be noted that the 0.4°C lower temperature of the molten glass at the entrance into the channel and 0.02% larger thermal uniformity factor can hardly be of significance in practical glassmaking. A more important advantage of the first variant appears in the computed melt temperatures. Thus, the average temperature of the molten glass in the tank before and after the threshold is 10.5°C and 11°C higher than for variant No. 2, and the average bottom temperature is 12.1 and 13.9°C higher, respectively, which makes it possible to decrease the glassmaking time by more than 3.5% .

At the same time the relatively simple construction of the masonry and the metal band of the melting tank as well as the smaller amounts of metal and expensive AZS refractory materials with 36 (41) % ZrO_2 used give the advantage to tanks with a smaller depth (1.7 m) of the fining zone, especially since the melt temperature can be increased by

$10 - 14^\circ\text{C}$ by increasing the thermal resistance of the bottom masonry. The variant No. 2 also has the advantage of unifying the structure of the bottom masonry.

To confirm the last conclusions we shall present the computational results for heat transfer in the fining zone with $\Delta x = 2.02$ and $\Delta h = 0.4$ m and the structure of the bottom masonry similar to that on the melting zone. For free-convection boundary conditions, the tank depth is taken into account in the calculation. For forced convection (see Table 3) the temperature of the inner surface of the bottom (1321.0°C) is given. For the free- and forced-convection conditions we obtain, respectively, $q_{\text{out}} = 1364.8$ and 1562.0 W/m^2 , $t_{\text{b}} = 1198.1$ and 1321.0°C , $t_{\text{out}} = 138.7$ and 148.8°C as well as the temperature gradient over the depth of the tank zones 127.8 and 55.5°C .

In summary, the computational results show that the given construction of the fining zone satisfies the requirements for the temperature of the bottom layer of the melt for free and forced convection. For both operating regimes of the melting tank the values of t_{b} are acceptable for long-term operation of all materials used in the masonry at the bottom of the tank (Fig. 6).

In closing we note that the results of the mathematical modeling of the internal heat and mass transfer make it possible to increase substantially the quality of the calculation and design of melting tanks. This creates objective prerequisites for attaining high energy efficiency and productivity for glassmaking furnaces.

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